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AN EVALUATION OF THE PRECISION AND ACCURACY OF PORTABLE FIELD SURVEY INSTRUMENT MEASUREMENTS OF URANIUM CONTAMINATION MEASUREMENTS ON SHOES

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SUMMARY

A major portion of the contamination control program being planned for the Oak Ridge Y-12 Plant* will be directed at assuring that employees do not exit the Plant with alpha contamination on the soles of their shoes in excess of 1000 disintegrations per minute per one hundred square centimeters (dpm/100 cm^2). Beta contamination would be similarly limited, probably at a higher level consistent with measurement capabilities. Measurements of shoe contamination are made using field survey instruments. Since these measurements are the key to monitoring the contamination control program, a study was conducted to determine the precision and accuracy of shoe contamination measurements using these instruments.

Trained Health Physics inspectors used their standard procedures to measure the alpha and beta activity of shoes which had been contaminated by walking through areas with removable uranium floor contaminations. Measurement precisions were determined from repeated measurements by five different operators using five alpha and five beta instruments to measure a number of shoes with varying contamination levels and enrichments. Measurement accuracies were determined by comparison with contamination levels measured in the Plant Laboratory using well-calibrated instrumentation.

The following conclusions were reached:

1. The standard deviations (S) of the measurements were estimated as a function of the measured contamination levels (M):

   $S = 0.36\ M$ (alpha),

   $S = 235 + 0.26\ M$ (beta),

   (S and M in dpm/100 cm^2).

   (Note that for a reading of 1000 dpm/100 cm^2, the standard deviation is 360 dpm/100 cm^2 for alpha measurements and 495 dpm/100 cm^2 for beta measurements.)

2. The survey instruments are biased high as used: alpha readings by a factor of 1.4, beta readings by a factor of 2.1.

3. To be 95% confident that no more than 1000 dpm/100 cm^2 alpha or beta activity is on the sole of a shoe, the hand-held alpha counter must read less than 300 dpm/100 cm^2, and the beta counter must read less than 100 dpm/100 cm^2.

*Operated for the U.S. Department of Energy by Union Carbide Corporation, Nuclear Division, under Contract W-7405-eng-26.

INTRODUCTION

The Y-12 Plant is undertaking to ensure that alpha contamination levels on materials, including employees' personal clothing, leaving the Plant are never greater than 1000 disintegration per minute per one hundred square centimeters (dpm/100 cm^2) direct. Beta contamination is to be similarly limited to levels consistent with measurement capability. A major portion of the contamination problem is contamination of the soles of employees' personal shoes and much of the effort to control contamination will be directed at shoe contamination. Much of this effort is dictated by our ability to measure. In fact, the 1000 dpm/100cm^2 level was selected because it was judged to be the lowest practical level that field instruments could measure. It is, therefore, extremely important to understand the capabilities of the field radiation monitoring instruments which will be used to evaluate the success of contamination control efforts. Capabilities of most importance are the accuracy and precision of these instruments for measuring alpha and beta activity on shoe soles.

The Ludlum Model 12 count rate meter with Model 43-4 air-proportional alpha probe is one of the primary instruments used for alpha radiation monitoring in the Y-12 Plant. The instrument package is a portable radiation survey meter designed for general field use. Four linear counting scales are used to cover the range 0-500,000 counts per minute (cpm). The Model 43-4 alpha probe is a low-volume static, air-proportional type operating at about 2000 volts. The probe window is 0.8 mg/cm^2 aluminized mylar with an active area of approximately 50 cm^2. Efficiency is approximately 30% of 2 emission with source at grill contact.

The Ludlum Model 2 count rate meter with Model 44-9 Pancake G.M. probe is a portable radiation survey meter used in Y-12 for beta radiation detection. The Model 2 is a portable meter similar to the Model 12, but with three linear ranges which are used to cover the count rate range of 0-50 kcpm. The Model 44-9 Pancake G.M. probe is a general-purpose, thin-window type. Window diameter is 2 inches, and the grill is approximately 71% open. Window construction is 1.5 to 2.0 mg/cm^2 mica. The detector is sensitive to alpha and beta/gamma radiation, however, a paper filter is used to screen out the alpha particles.

An experiment was designed to determine the precision and accuracy of the survey instruments when measuring the contamination levels of shoe soles. In this experiment, several pairs of standard work shoes were equipped with paper cutouts on the soles. These cutouts were then contaminated in the uranium processing areas in the Plant. While the cutouts were still attached to the shoes, a number of Health Physics technicians measured the levels of alpha and beta emissions on the shoes. The cutouts were then removed and sent to the Plant Laboratory for analysis on equipment generally used to measure alpha and beta levels on filter paper. After all this was done, a statistical analysis of all the data estimated the precision and accuracy of the field instruments.

THE EXPERIMENTAL DESIGN

Eleven participants procured new Company safety shoes for use in the study. Clean blotter paper was cut to the outline of each shoe's sole and attached to it with two-sided tape so that the contour of the bottom of the shoe was maintained. Eight pairs of the shoes were then worn in the hallways outside offices in Building 9212 and building 9723-25 with the blotter-paper soles attached. Two other pairs were worn in the Press Area of Building 9204-4, and one pair was worn in the hallways of Building 9711-1. The wearers were instructed to take different numbers of steps in each pair of shoes so that a range of levels of contamination would be available for the study. The blotter-paper soles remained attached to the shoes for the portion of the experiment involving measurement of contamination with field instruments.

Measurements conducted by five technicians using hand-held instruments were scheduled in such a way that statistical requirements for random character of the experimental design were met. Each technician was assigned a particular instrument pair (one for the determination of alpha activity, and one for beta) for use throughout the experiment, so that technician and instrument errors were statistically confounded. Each day of the week was divided into four two-hour segments, and each segment was assigned to a technician for measuring contamination on the shoes. The assignment of these time segments was made randomly by drawing the names of the technician from a lottery. Identifying symbols attached to the twenty-two shoes were changed daily to minimize the possibility that technicians might introduce bias into their measurements by recognizing patterns in the levels of contamination being measured. Pattern recognition was further confused by mixing the shoes as they lay on the table each day. A standardized form for collecting data was prepared and distributed to the participants each day. Besides alpha and beta measurements on the shoes, the operators were required to provide background readings before, during, and after the measurements were made.

After all of the technicians' measurements on the shoes were completed, the twenty-two pairs of paper shoe-sole cutouts were removed from the shoes and the area (cm^2) of each was determined. Each cutout was then divided into six or seven pieces (depending on the size of the shoe) so that alpha and beta measurements could be made in the Plant Laboratory with a modified Sharp Lowbeta Counter. Three pieces of each cutout were measured for alpha and beta on instrument #1, and the remaining pieces on instrument #2. On each of three days, one measurement of alpha and one measurement of beta were made on each piece, resulting in a total of three measurements on each piece. An overall measurement on a shoe was found by adding the individual pieces' readings on a day together and correcting for the cutout size to get $dpm/100cm^2$. In all, three overall laboratory alpha and beta measurements per shoe were obtained. In addition, one set of beta measurements were taken with the detector shielded with a 0.9 mil aluminum foil. This prevented any alphas from being detected, thus, completely eliminating alpha cross talk into the beta channel.

The five field alpha meters were taken to the 9983 calibration station for further analysis in an effort to distinguish between operator and counter variability. Each counter was attached to a device that recorded the movement of the meter needle on moving graph paper. Four known alpha sources (466, 1180, 3782, and 19296 dpm) were measured twice by each of the five counters in a random order while attached to the graphing device. The level-off point on the graphs determined the alpha readings, and the time till level-off was noted. No similar experiment was run on beta meters since no beta standards were available.

RESULTS OF THE STATISTICAL ANALYSIS

Three data sets, obtained from the experiment, were the hand-held counter measurements on the shoe-sole cutouts made by the five technicians, the laboratory measurements on the pieces of the shoe-sole cutouts, and the hand-held counter measurements on the known alpha standards. The key results of the statistical analyses of these data are listed below:

1. The variability in measurements made by the technicians using the hand-held counters is a function of the type of contamination and increases with the level of contamination on the shoes. Estimates of the relationships are given by

$$S = 0.362 * M \qquad \text{(alpha)},$$

$$S = 235 + 0.26 * M \quad \text{(beta)},$$

where

S = the standard deviation of a measurement, and
M = the measured contamination level on the shoe in $dpm/100cm^2$.

2. The measurements made by the technicians on the shoes were approximately twice as variable as those made with the same counters on the standards. The extra variability may be due to the technicians or the geometry of the shoes.

3. The alpha and beta readings by the hand-held counters were both biased high. The alpha $dpm/100cm^2$ readings made by the hand-held counters were approximately 1.4 times both the laboratory values for the shoes and the labeled dpm values on the standards. The beta $dpm/100cm^2$ readings by the hand-held counters were approximately 2.1 times the laboratory values.

4. There were no significant technician-to-technician differences detected in alpha measurements made with the hand-held counters, but one of the technicians showed significantly higher beta measurements than the other four.

5. The hand-held counters detected no significant shoe-to-shoe differences within any of the pairs of shoes. The laboratory measurements, with their greater precision, detected shoe differences within every pair.

6. The level-off time for the hand-held counters ranged from 15 to 30 seconds.

7. The alpha measurement variabilities of the two laboratory instruments appeared to be negligible when compared to the variability of the radiation source. The beta measurement variabilities were larger than the alpha measurement variabilies, but were still quite small.

Figure 1 shows the hand-held counter alpha readings on the eleven pairs of shoes: 1-2, 3-4, 5-6, ..., 21-22. Figures 2 & 3 show the beta readings. Notice in both plots that the variability in the readings increases with the contamination level. The two pairs of shoes that were worn in the 9204-4 Press Area are shoes 1-4. They are much more contaminated than the other 18 shoes. It is apparent in these plots that the measurements are too variable to detect differences between contamination levels in the two shoes making a pair.

Figure 4 is a graph of average hand-held counter alpha readings versus average laboratory alpha readings. Each point represents one shoe. Shoes 1-4 are not included in this graph. Figure 5 is the corresponding plot including shoes 1-4. A straight-line fit of the data in Figure 4 has the hand-held counter readings being approximately 1.4 times the laboratory readings and zero intercept. The lack of a significant intercept reveals that the inaccuracy of the hand-held counters is most likely due to an incorrect correction factor (multiplicative), not an overall bias of the counters. In Figure 5, the straight-line fit yields approximately the same 1.4 constant, but this time the intercept is significant.

The corresponding hand-held versus laboratory plots on the beta data are found in Figures 6 and 7. The straight line fit in Figure 6 has the hand-held counter readings being approximately 2.1 times the laboratory readings with no significant intercept. The slope in Figure 7 is the same, but the intercept is significant. A supplementary laboratory study showed that the laboratory beta readings included some alpha counts. When the alpha was properly shielded, the intercept disappeared.

The two areas in which shoes were worn show different relationships between the alpha readings and the beta readings. Based only on the laboratory measurements on the shoes, Figure 8 is a plot of average alpha versus average beta dpm/100cm^2. Again, each point represents one shoe. A straight-line fit of the four points corresponding to shoes 1-4 gives the relationship: alpha = 0.17 * beta. The straight-line fit of the remaining 18 shoes gives the relationship: alpha = 2.2 * beta. This difference in the alpha and beta relationship for the two areas is not suprising since there are characteristically different contamination sources in the two areas.

Figure 1

HAND-HELD COUNTER ALPHA dpm/100cm^2 READINGS

(All Shoes)

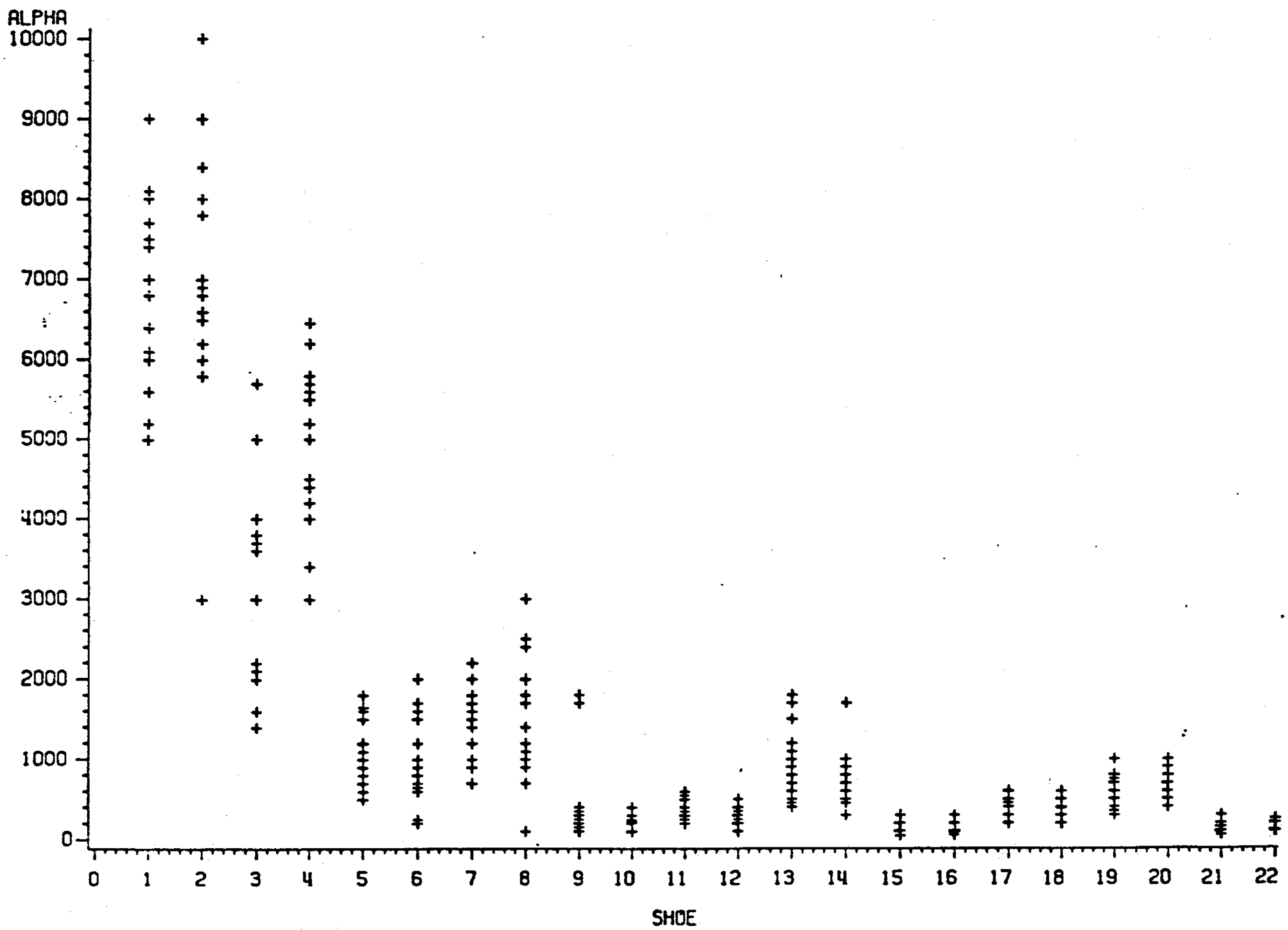
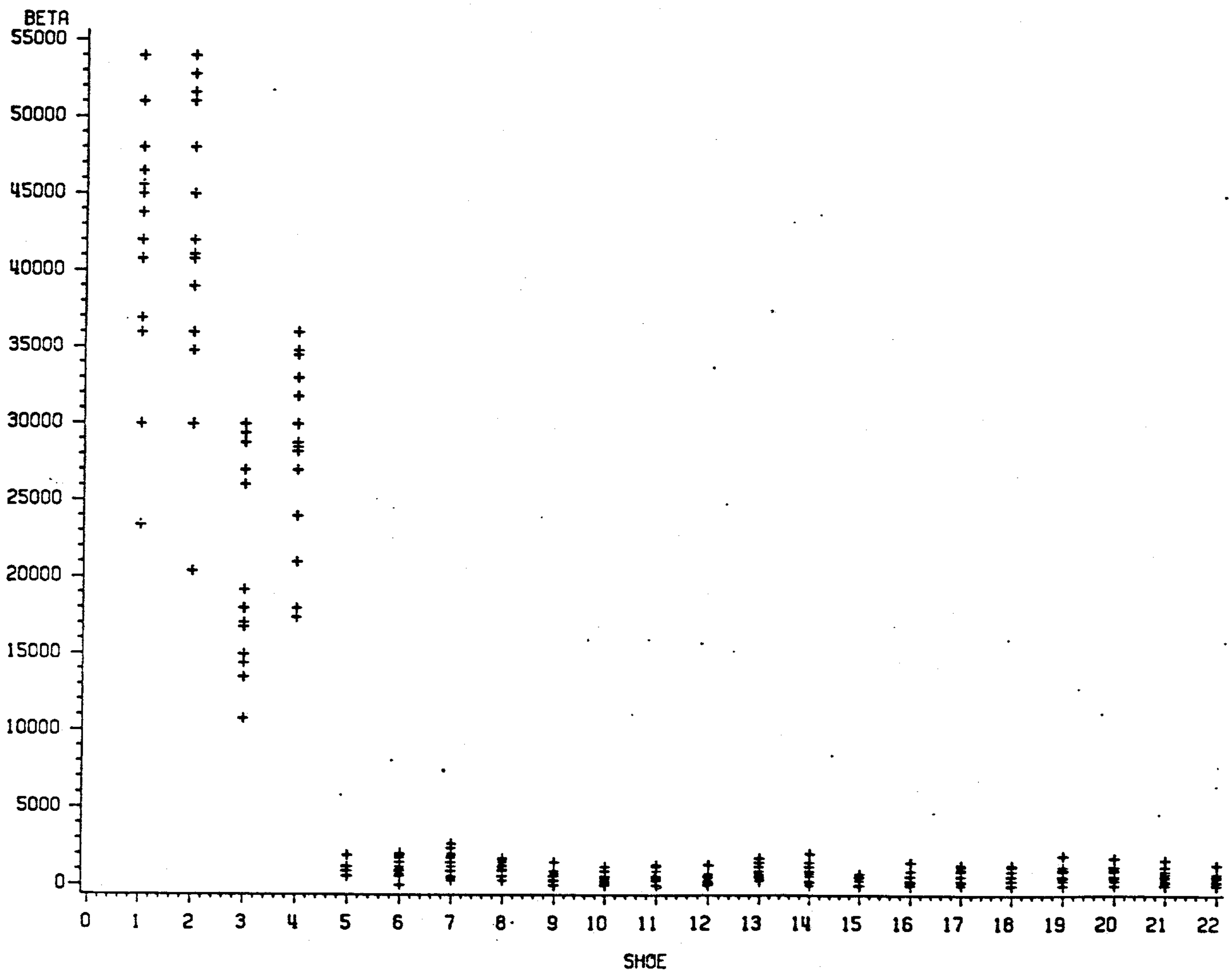


Figure 2

HANDâHELD COUNTER BETA dpm/100cm² READINGS[1]

(All Shoes)



[1]See Figure 3 for an enlargement on Shoes 5-22.

Figure 3

HAND-HELD COUNTER BETA dpm/100cm^2 READINGS

(Shoes 5-22)

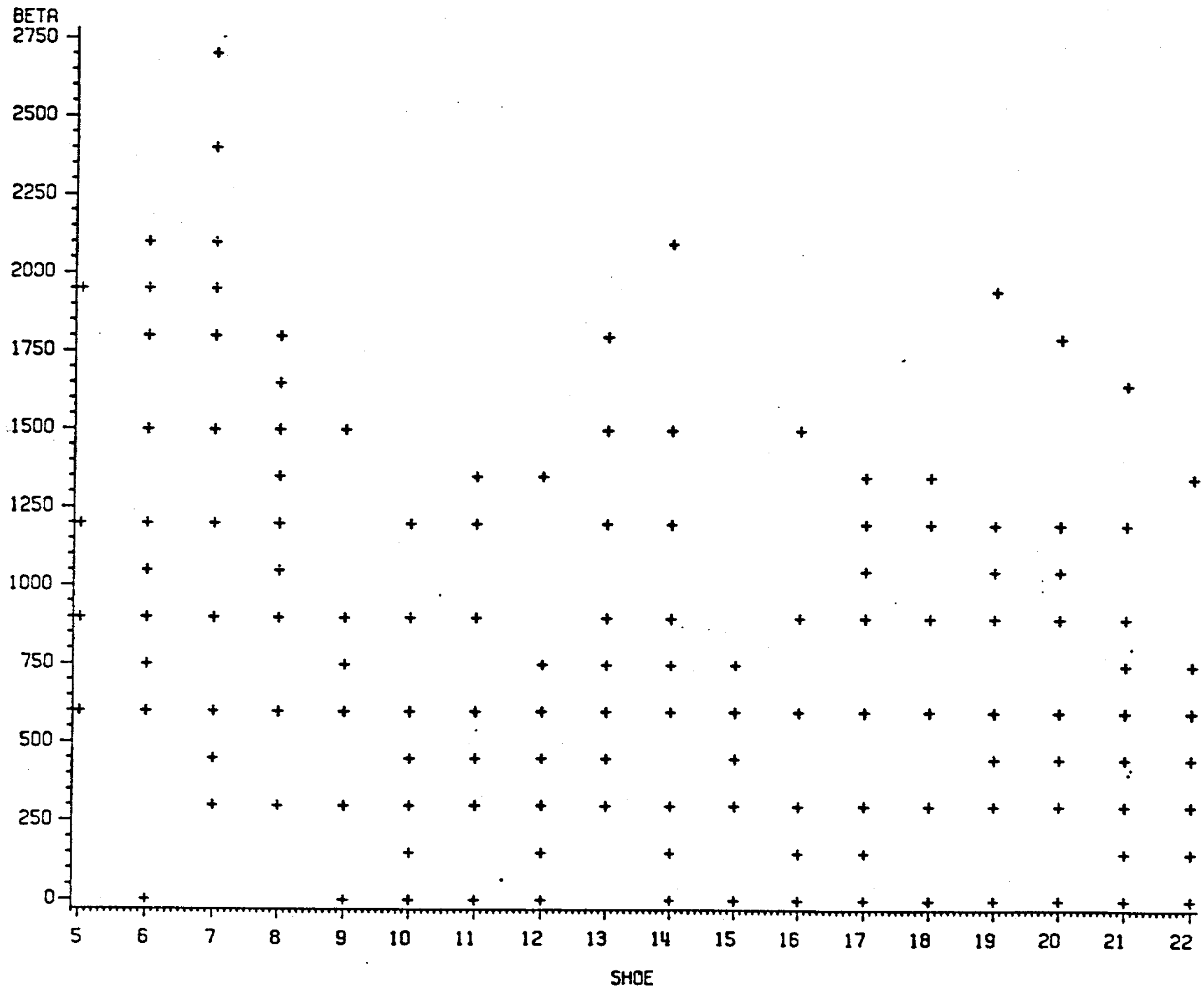
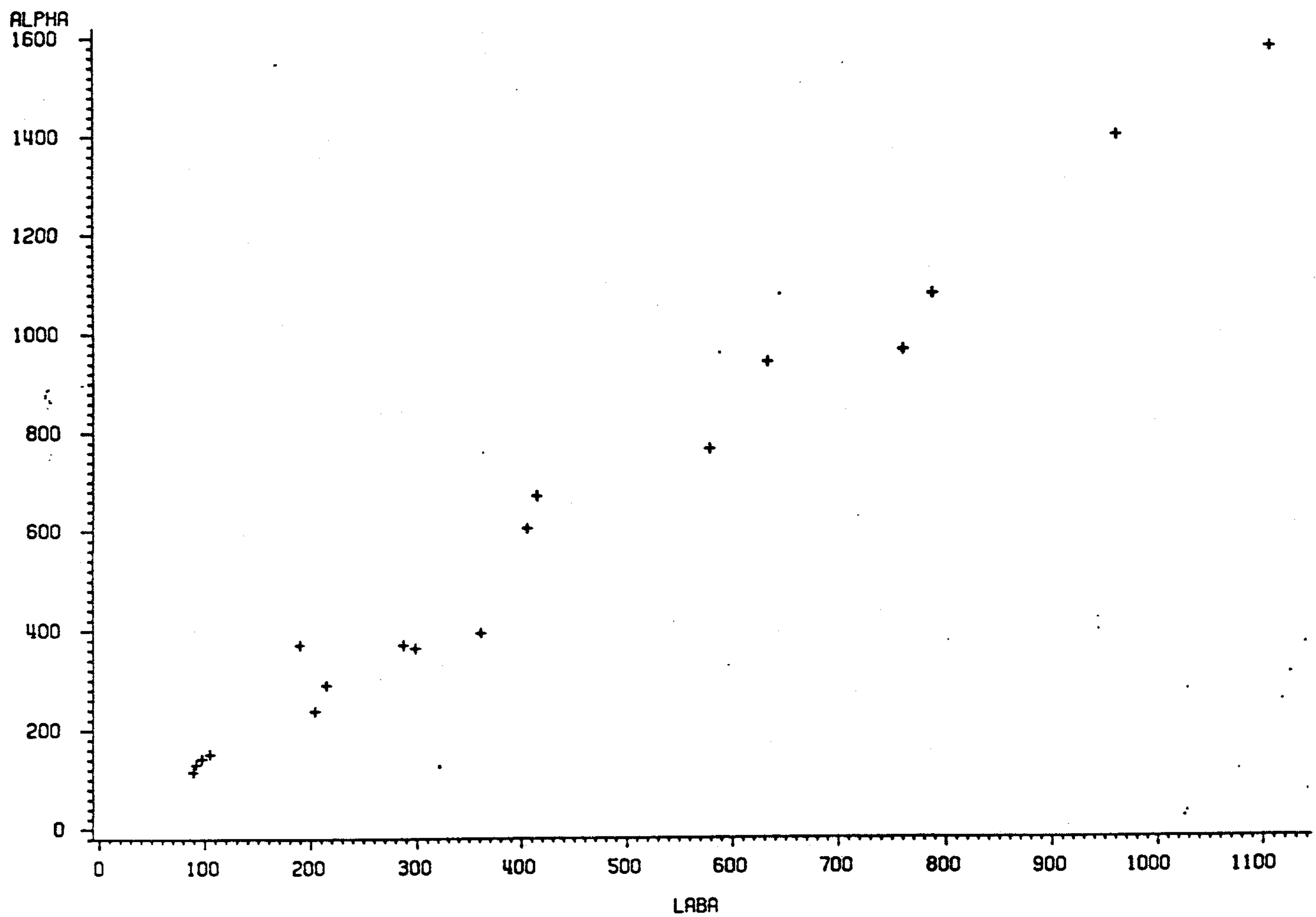


Figure 4

HAND-HELD COUNTER[1] VERSUS LABORATORY[2] ALPHA dpm/100cm[2]

(Shoes 5-22)



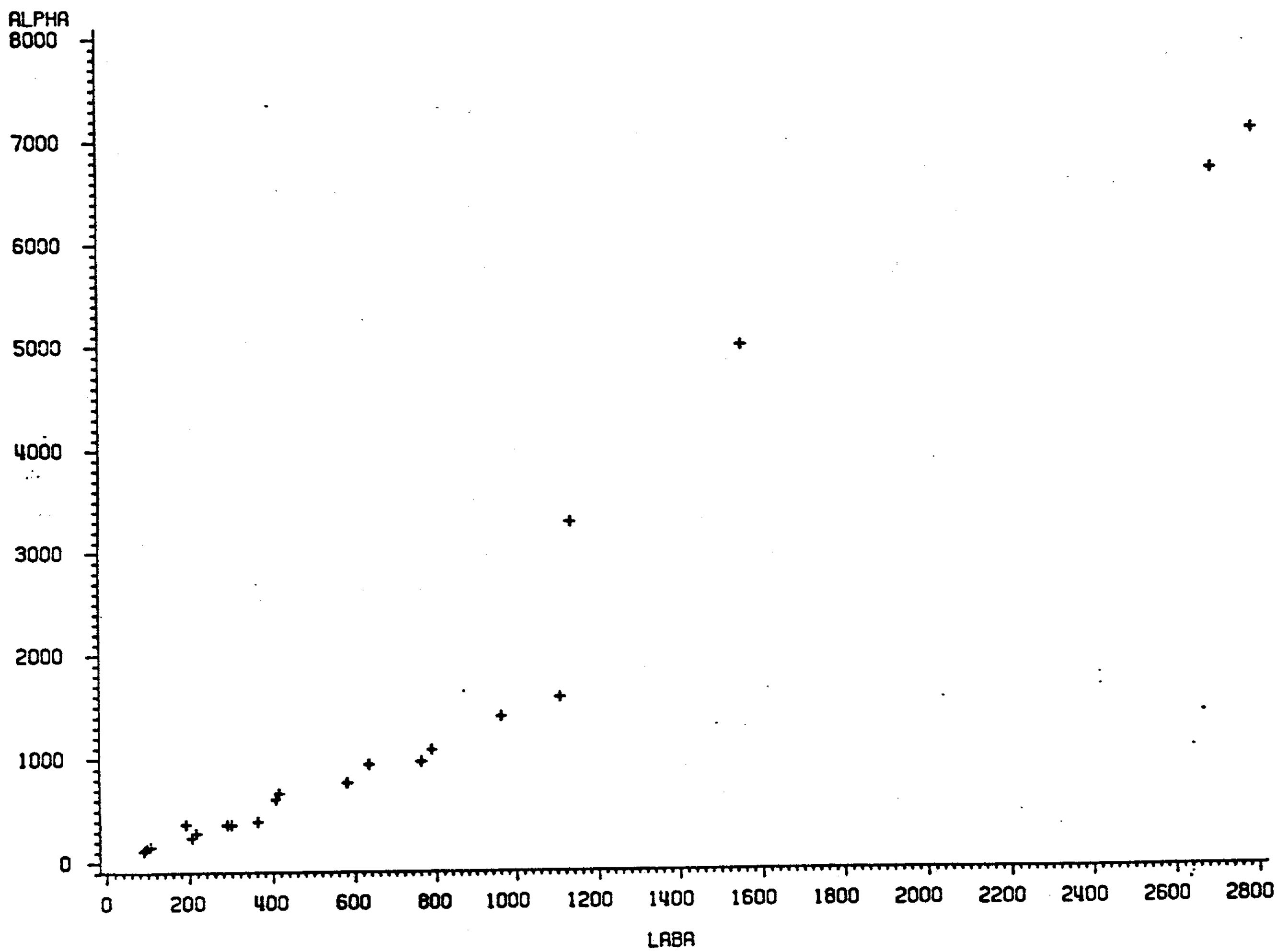
[1]ALPHA = Hand-held Counter Alpha.

[2]LABA = Laboratory Alpha.

Figure 5

HAND-HELD COUNTER[1] VERSUS LABORATORY[2] ALPHA dpm /100 cm^2

(All Shoes)



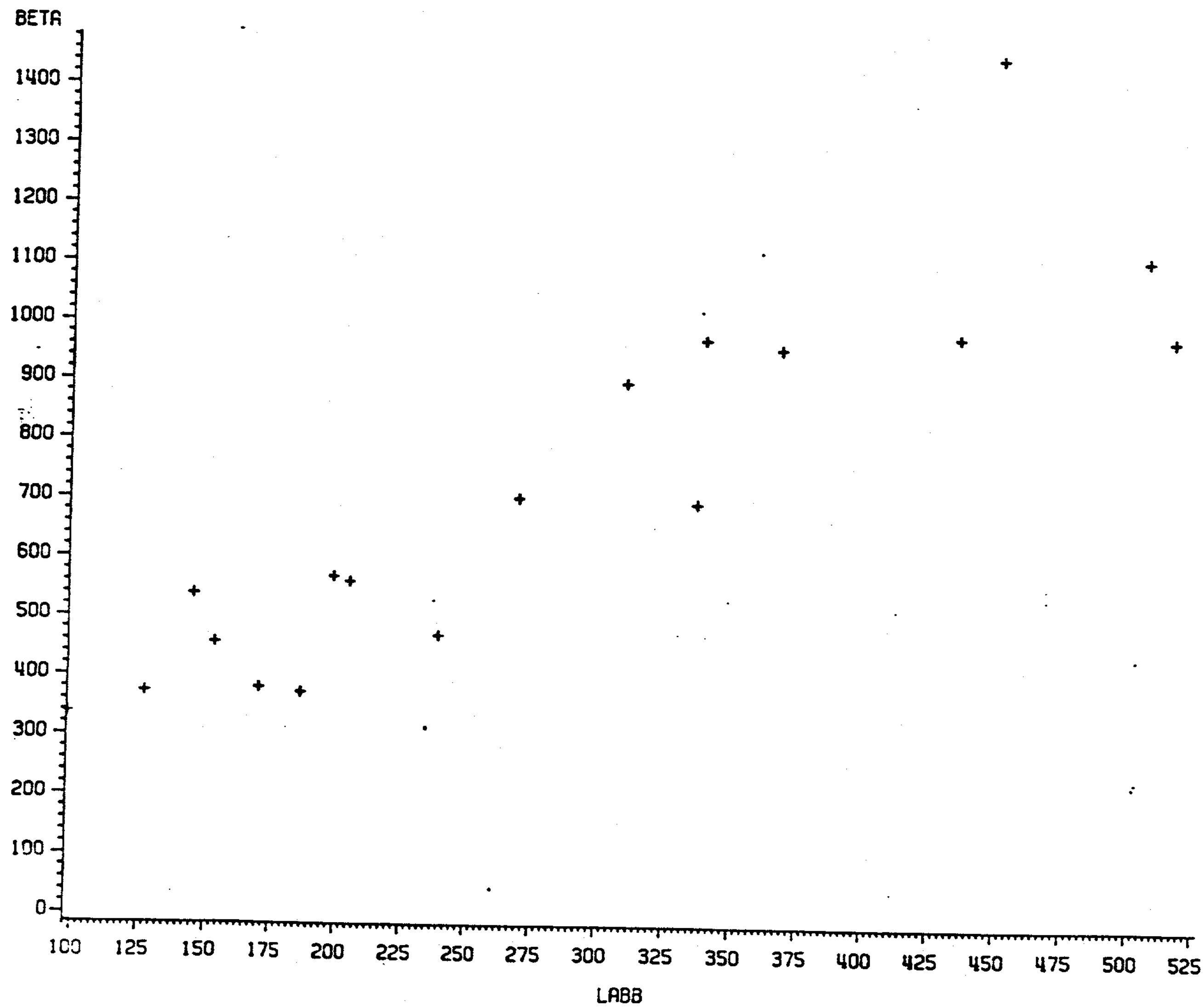
[1]ALPHA = Hand-held Counter Alpha.

[2]LABA = Laboratory Alpha.

Figure 6

HAND-HELD COUNTER[1] VERSUS LABORATORY[2] BETA dpm/100cm²

(Shoes 5-22)



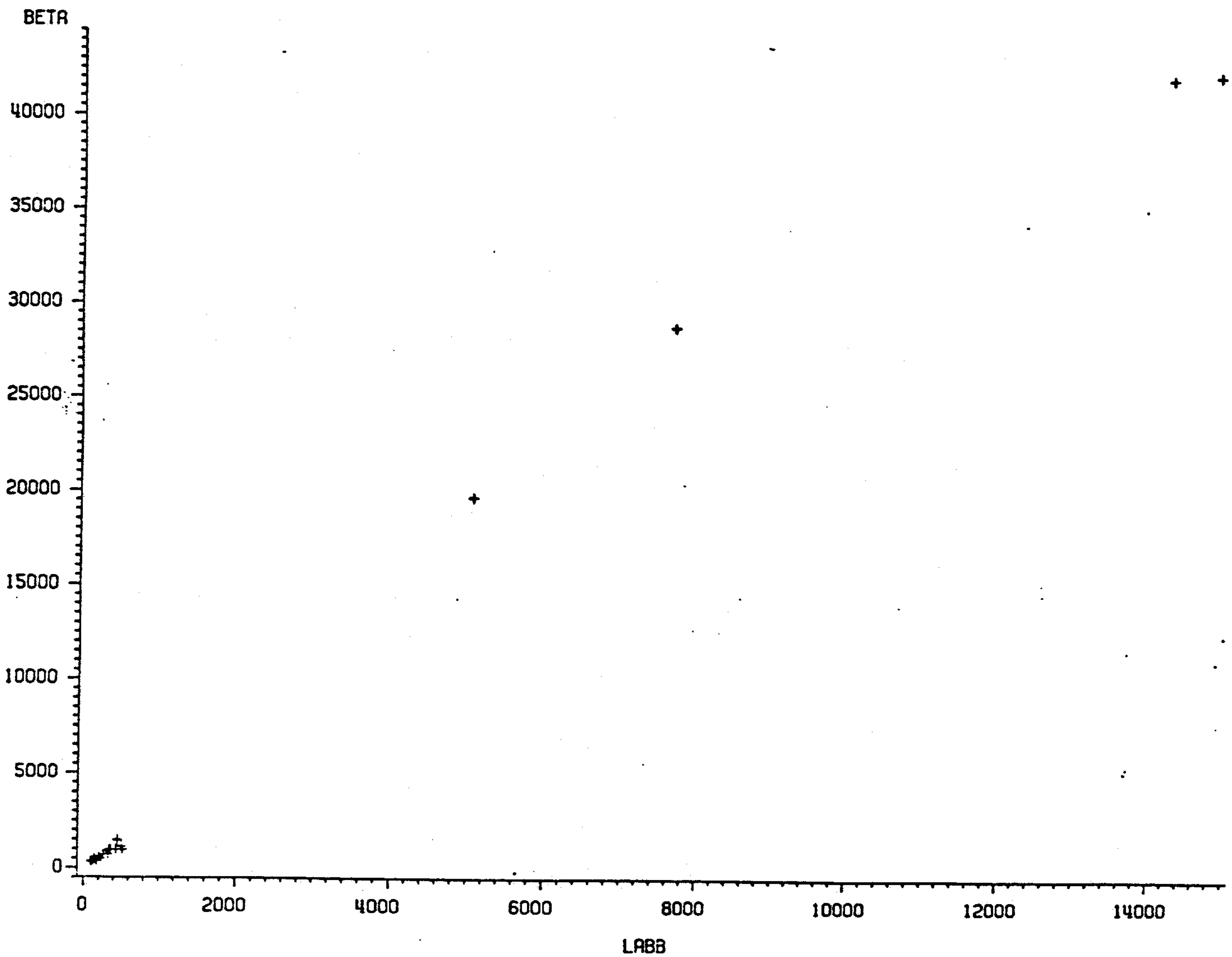
[1]BETA = Hand-held Counter Beta.

[2]LABB = Laboratory Beta.

Figure 7

HAND-HELD COUNTER[1] VERSUS LABORATORY[2] BETA dpm/100cm^2

(All Shoes)



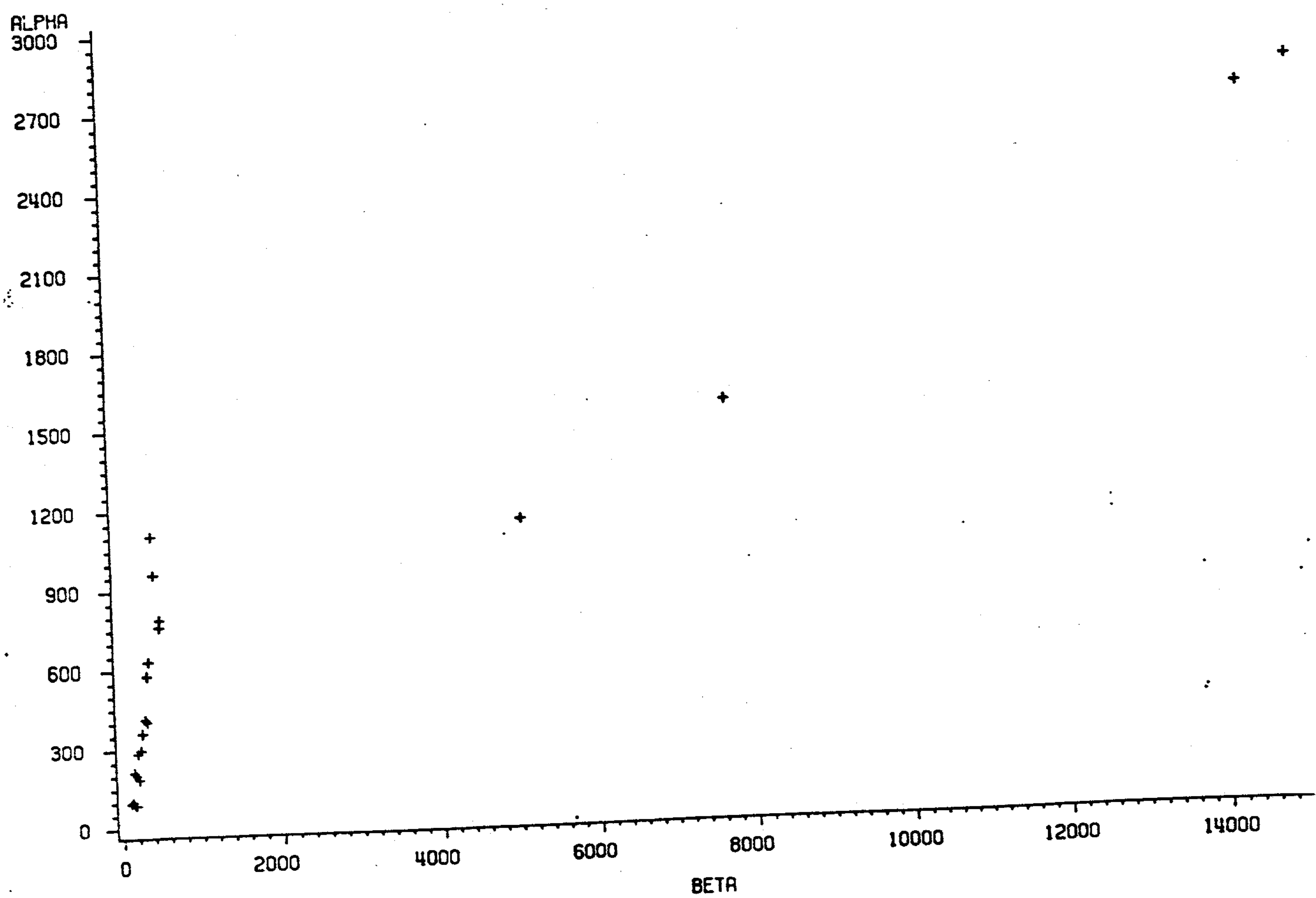
[1]BETA = Hand-held Beta.

[2]LABB = Laboratory Beta.

Figure 8

LABORATORY ALPHA VERSUS LABORATORY BETA dpm/100cm^2

(All Shoes)



CONCLUSIONS AND RECOMMENDATIONS

There is a high degree of variability in the beta measurements made by the hand-held counters on the shoes. It was found in this analysis that more precise beta measurements on shoes worn in the 9212 corridor could be made by using the formula:

$$\text{beta} = 120 + 0.27 * \text{alpha},$$

where

alpha = the alpha dpm/100cm^2 reading made by the hand-held counter.

Similarly, on shoes worn in the 9204-04 Press Area, an equivalent formula could be found after more experimentation. This suggests that measurements on shoes using beta counters are unnecessary for areas where the alpha to beta relationship is known.

There is some interest in using hand-held counters to determine whether a shoe sole contains more than 1000 dpm/100cm^2 of alpha or beta. In order to be at least 95% confident that at most 1000 dpm/100cm^2 of alpha is on a shoe, a hand-held alpha counter must read less than 300 dpm/100cm^2. For beta, a beta counter must read less than 100 dpm/100cm^2 which differs from zero by much less than one standard deviation so that uncontaminated shoes would routinely produce readings greater than this value.

APPENDIX

Instrument Descriptions

Alpha Survey Instrument

The Ludlum Model 12 count rate meter with Model 43-4 air-proportional alpha probe is one of the primary instruments used for alpha radiation monitoring in the Y-12 Plant.

The instrument package is a portable radiation survey meter designed for general field use. Four linear counting scales are used to cover the range 0 - 500 counts/minute, with multiples of X 1, X 10, X 100, and X 1K. Meter time constant is: fast response, 3 seconds; slow response, 11 seconds. The instrument is provided with a reset button for rapid meter zeroing. Later models are equipped with an audio output.

The Model 43-4 alpha probe is a low-volume static, air-proportional type operating at about 2000 volts. Detector input sensitivity is set at $2^{-}\pi$ millivolts. Probe window is 0.8 mg/cm^2 aluminized mylar with an active area of approximately 50 cm^2. Efficiency is approximately 30% of 2 emission with source at grill contact.

Calibration pots are located on the intrument cover in line with the multiplier index of each scale. True reading calibration for each scale is determined with a pulse generator. This calibration is correlated to detected radiation value by gain adjustment to 100% of 2 π emission using plated uranium alpha standards traceable to the National Bureau of Standards.

To use the alpha instrument, a technician will first determine the background for this instrument. The background will be characteristic of a particular instrument and not the environment in which it is being used. Most of the background is caused by contamination of the probe and will slowly increase as the instrument is used to survey contaminated materials. The background reading is determined by setting the selector knob on the lowest scale (X 1) and letting the needle stabilize. After noting the background, a technician will survey an object by placing the probe on the object (ideally, at a place on the object flat enough to cover the entire probe) and setting the multiplier to the scale with which the needle provides the largest on-scale reading. The technician then estimates the gross counts by multiplying the meter reading by the multiplier. Background is subtracted, and the result is multiplied by two to get the number of alpha disintergrations per minute per 100 cm^2.

During these experiments, several tests were run on the alpha probes in order to better understand the reliability of these instruments.

One test was to check the consistency of five of these instruments with some plated alpha standards. A strip chart recorder was attached to the meter in order to record the voltage across the needle as a function of time. This recorder caused no detectable difference in the meter reading. With this setup, the level-off point of the meters and the time to the level off point could be measured. The results of these measurements were mentioned in the Conclusions and Results section.

Three alpha instruments were checked with a 58 kdpm beta source in order to determine if any beta particles would be counted. With each instrument no betas were counted. The meter reading and audio count rates did not increase above background levels.

A 0.15 μCi ^{241}Am alpha source was checked with and without this same 58 kdpm beta source near the detector to determine whether the presence of a beta source might alter an alpha reading. There was no detectable difference in the alpha readings when the detector was exposed to the alpha source alone and when exposed to the alpha source along with the beta source.

Beta Survey Instrument

The Ludlum Model 2 count rate meter with Model 44-9 Pancake G.M. probe is a portable radiation survey meter used in Y-12 for beta radiation detection. This counter is used in addition to the standard CDV-700 and CDV-493 type thin-wall (30 mg/cm^2) G.M. counters.

The Model 2 is equipped with 3 linear ranges from 0-50K counts/minute. Meter scale presentation is 0-5K counts/minute with multiples of X .1, X 1, and X 10. Meter response time constant is switchable for 3 or 11 seconds. All units have a built-in audio with ON/OFF switch. High voltage is externally adjustable from 400 to 1500 volts. Input sensitivity is 40 millivolts.

The Model 44-9 Pancake G.M. probe is a general-purpose, thin-window type. Window diamter is 2 inches, and the grill is approximately 71% open. Window construction is 1.5 to 2.0 mg/cm^2 mica. The detector is sensitive to alpha and beta/gamma radiation with an operating point of 900 volts at the instrument connector.

The counts-per-minute scale is calibrated to true reading with a pulse generator. The instrument is then exposed to a calibrated gamma source (^{137}Cs), and the exposure reference points are noted for each range/scale. In Y-12, these instruments are then normalized to a plated natural uranium disk source with activity of 7500 dpm beta.

The alpha and beta activity of the source was determined by the Y-12 Plant Laboratory. These instruments are generally used with an alpha-shielding paper facing over the probe detector window and grill. Normalization is checked with this paper shield in place. An "instrument multiplication factor" of 6 is used to adjust for detector efficiency.

A technician will determine the background level on this meter by setting the multiplier to 0.1, the lowest scale, and then letting the needle stabilize. When a survey is performed, the net reading in counts is determined just as it is with the alpha meter. The reading in dpm per $100cm^2$ is estimated by multiplying the net counts by 30. This factor is derived from the area of the probe (a factor of 5 less than $100cm^2$) and the efficiency of the probe (which is 16.7%).

Laboratory Instrumentation

A modified Sharp Lowbeta Counter, Model ES105, was used to count the paper samples from the shoe experiment. This instrument consists of two thin window (800 $\mu g/cm^2$) gas flow detectors, a guard detector and anticoincidence circuitry for rejection of cosmic ray background, a lead shield to minimize environmental background, and appropriate electronics for operation and control.

The instrument utilizes pulse height discriminators to set up windows for simultaneous counting of alpha and beta radiation. This is possible since beta particles produce much smaller pulses than alpha particles.

The detectors are operated at approximately 1800 volts using P-10 (90% argon - 10% methane) as the detector gas. The alpha and beta efficiencies are approximately 30 percent and 40 percent, respectively, for ^{99}Tc betas and uranium alphas, from electroplated metal standards.

The instrument is calibrated for alphas by counting a uranium standard which is traceable to the NBS. The instrument is standardized for counting betas by counting a ^{99}Tc source which emits betas only and to which all other beta counts are compared. The following mathematical relationships are important to the operation of the instrument. Explanations of beta backscatter and alpha crosstalk follow.

1) $$\text{Alpha dpm} = \frac{C_\alpha - b_\alpha}{E_\alpha\ t},$$

Alpha dpm = Alpha disintegrations per minute.
C_α = Alpha count.
b_α = Alpha counter background.
E_α = Alpha counter efficiency.
t = Count time.

2) Beta dpm $= \dfrac{C\beta - b\beta}{E\beta\ f\beta\ t}$,

Beta dpm = Beta disintegrations per minute,
$C\beta$ = Beta count,
$b\beta$ = Beta counter background,
$E\beta$ = Beta counter efficiency,
$f\beta$ = Backscatter factor,
t = Count time.

3) When correcting for alpha crosstalk in the beta channel:

$$\text{Beta dpm} = \frac{C\beta - b\beta \ - \ fc\ (C\alpha - b\alpha)}{E\beta\ f\beta\ t},$$

fc = crosstalk factor,
The other terms are defined above.

4) Counter efficiency $= \dfrac{Cs - bs}{S}$,

Cs = Standard counts per minute,
bs = Counter background (counts per minute),
S = Standard value (disintegrations per minute).

This equation is used for both beta and alpha efficiency.

Consider the geometry of particles being emitted from a flat surface. Assuming they are emitted in random directions, one-half will move away from the surface and thus can potentially be counted. The other half will be lost back into the surface material and, in general, will not be detectable by counting; however, of those "lost" particles, a certain percentage will be scattered back out of the material, and thus actually are available for counting. This mechanism is termed backscatter. Backscatter depends primarily upon the type of particle, its energy, and the material upon which it is deposited. Generally, for alpha particles, the backscatter term is small and may be ignored. For beta particles, it is much more significant and must be taken into consideration when calculating counter efficiencies.

For the present case of using a ^{99}Tc beta standard on stainless steel to calibrate for betas on paper, the correction is as follows:

Backscatter factor for stainless steel = 1.50,
Backscatter factor for paper = 1.10,

Correction factor $= \dfrac{1.10}{1.50} = .73.$

Thus, the counter efficiency, as determined from ^{99}Tc on stainless steel, must be corrected by this factor when used to calculate results from betas on paper.

It is possible to set up a proportional counter so it can be used for simultaneous counting of alpha and beta particles. This can be accomplished because of the fact that alpha particles produce detector pulses which are much larger than those from beta particles. By using pulse height discrimination, pulses from the two can be separated reasonably well.

However, because some alpha particles are scattered and degraded in energy, they unavoidably fall into the beta pulse region and are counted as beta. This does not prevent achieving a correct alpha count since the alpha efficiency calibration corrects for the losses; however, it does cause the beta result to be biased high. This alpha interference with the beta count is termed alpha crosstalk.

It is possible to correct the beta count for alpha crosstalk if a standard can be prepared which closely approximates the sample in alpha energy and solids content, among other things. In practice this is difficult, and the best correction is only a good approximation.

The alpha crosstalk factor is defined as:

$$fc = \frac{C\alpha'}{C\alpha},$$

fc = Alpha crosstalk factor,
$C\alpha$ = Alpha counts falling into the alpha channel, and
$C\alpha'$ = Alpha counts falling into the beta channel when a pure alpha standard such as ^{210}Po is counted.